An Overview of JPL's Advanced Propulsion Concepts Research Program

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Jet Propulsion Laboratory

California Institute of Technology

April 3, 2001

The Advanced Propulsion Technology Group Fulfills Two Roles

17 Engineers

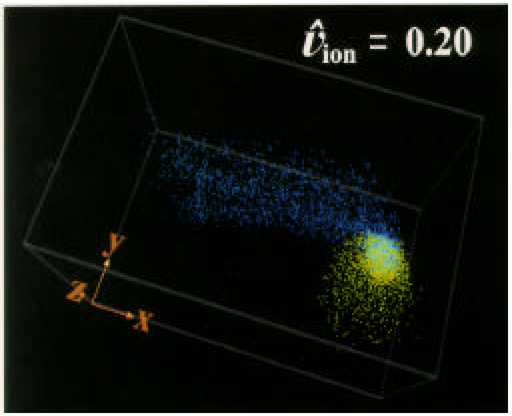
- 14 with or completing PhD's
- 3 with or completing MS's
- 222 years total experience

3 Technicians

- 105 years total experience

Unique Facilities

4 Large Vacuum Facilities and a Number of Smaller Chambers



Advanced Analytical Capabilities

Plasma Simulation Tools Using High Performance Supercomputers

Near-Term Electric Propulsion Program

Goal: Implement advanced propulsion in JPL missions

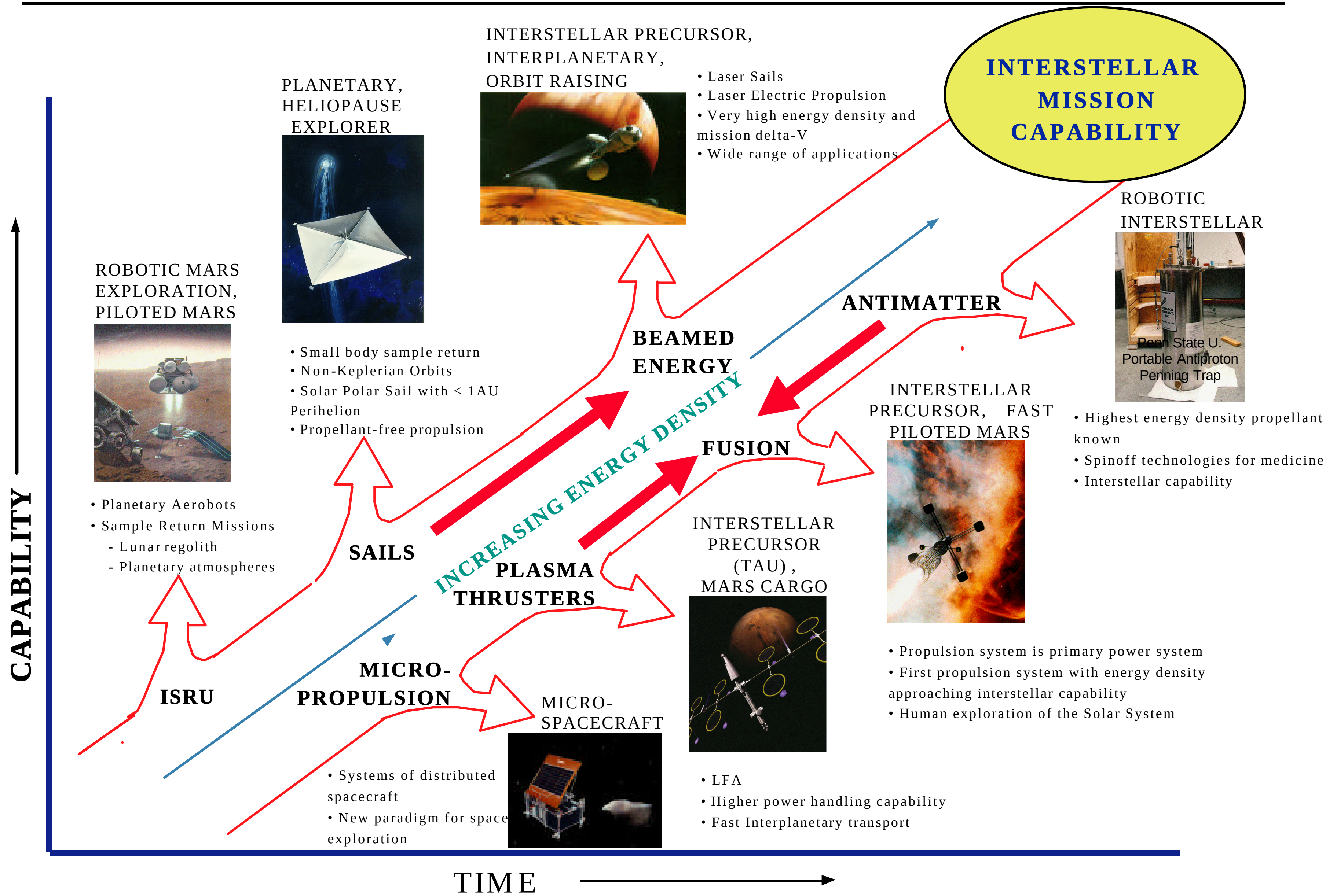
- Primary and auxiliary solar electric propulsion systems
- Mission/systems analysis
- Technology validation
- Advanced technologies

Advanced Propulsion Concepts Program

Goal: Assess feasibility of new technologies which might enable exciting new missions

- Micropropulsion
- Solar sails
- High power plasma propulsion
- Fusion propulsion
- Antimatter propulsion
- Mission/systems analysis
- Computer simulations

The Road to the Stars: Deep Space Advanced Propulsion

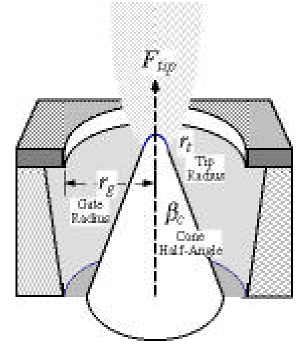


FY01 Program Content Spans the Range of Advanced Propulsion Concepts

- **Micropropulsion**
  - Revolutionary Cathode Technology
  - Vacuum Arc Plasma Sources (JPL, Caltech, AASC and LBL)
  - Laser Ablation Thrusters
- **Propellantless Propulsion**
  - Solar Sails (JPL and MIT)
  - Microwave Sails (JPL, Microwave Sciences and UC Irvine)
- **Electromagnetic Propulsion**
  - NEP Mission and Systems Analysis
  - Lithium-fed Lorentz Force Accelerators (JPL, Princeton and MSFC)
  - Diamond Film Growth Using Magnetoplasmadynamic Chemical Vapor Deposition (JPL and Caltech)
- **Fusion/Antimatter Propulsion**
  - ICAN Target and Systems Study (LLNL)
  - Beam Core Antimatter Rocket Systems Study
  - Magnetized Target Fusion Systems Study (JPL and MSFC)
- **The Advanced Propulsion Concepts Website**

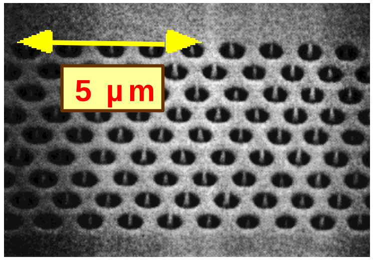
Micro-Fabricated Field Emission Cathodes: A Technology with Tremendous Potential

- **Arrays of micro-machined tips and gate electrodes produce high electron current densities by field emission**
  - Enabling technology for micro-gas discharges for micropropulsion applications
  - Propellantless current emission for tether applications
  - Cold cathode technologies enable use of reactive propellants such as oxygen

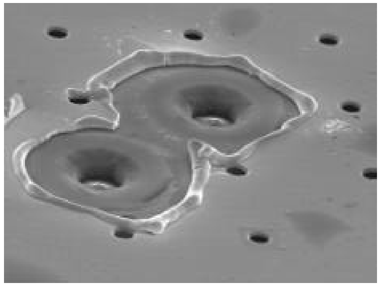


Geometry of a single emitter tip

Array of field emitter tips

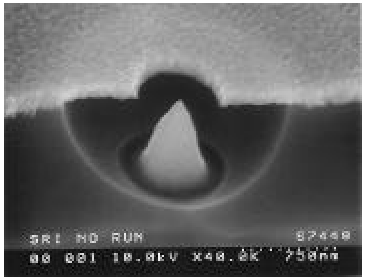


- **Propulsion applications demand emitter array operation in gas discharges or ambient plasma environments**
  - Increased risk of arcing
  - Sputter erosion of tiny structures
  - Space charge limitations in tenuous gas environments



Arcing damage to tips and gate electrode

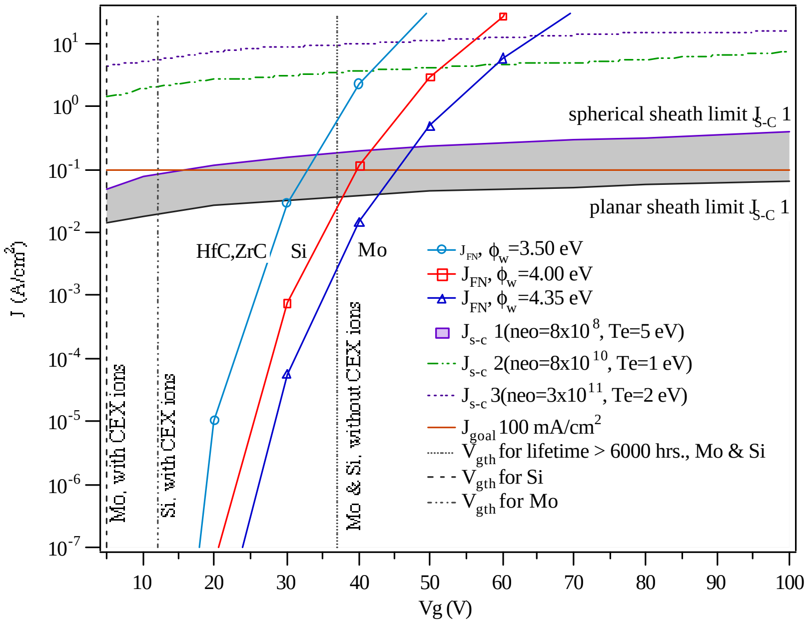
Dulling of emitter tip due to ion sputtering

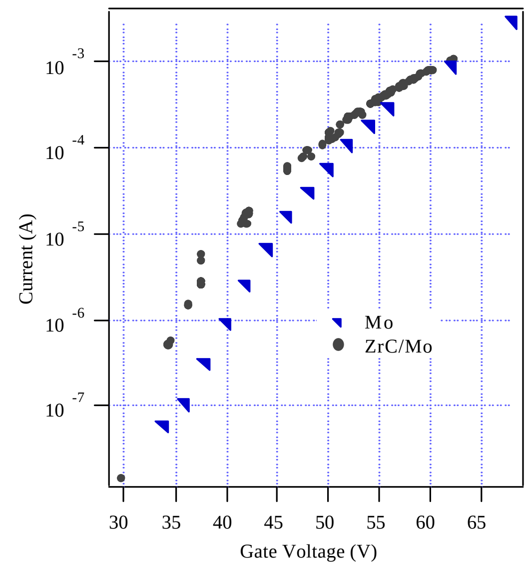


- **Technical approaches:**
  - Smaller scale structures
  - Current-limiting architectures
  - New materials
  - Electrode designs to filter out ions

Performance Comparison of Mo and ZrC/Mo FEA Cathodes in Xenon Environments

Performance and life models suggest carbide-coated Mo cathodes can meet micropropulsion requirements

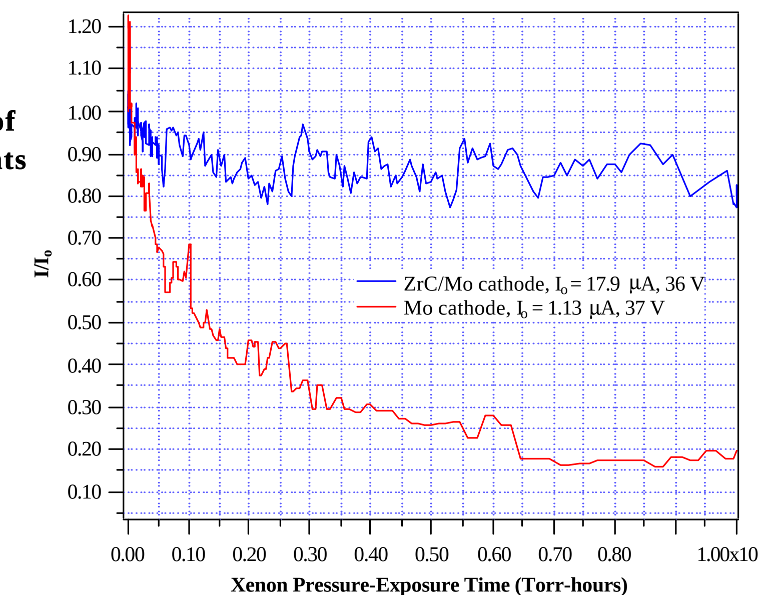




Comparison of Mo and ZrC/Mo cathodes confirms higher performance due to lower work function

Exposure tests show greater stability of ZrC/Mo cathodes in xenon environments compared to Mo cathodes

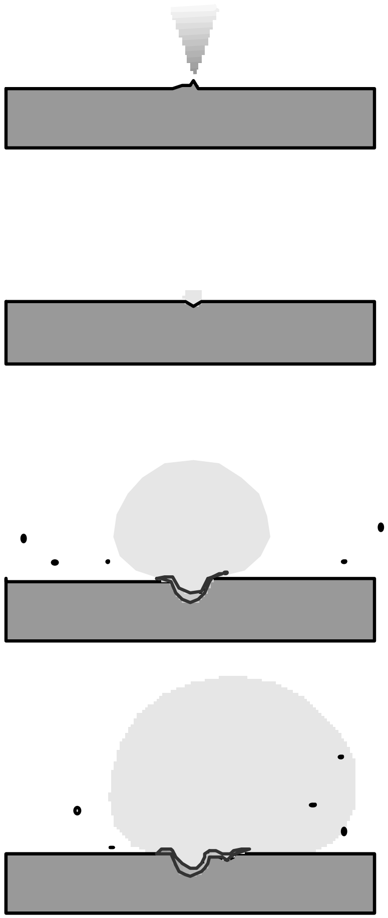
FEA Cathodes
50,000 tip
0.95 μm gate aperture diameters
ZrC/Mo Cathode
36 V gate voltage
100 V anode voltage
Mo Cathode
37 V gate voltage
60 V anode voltage



JPL TECHNICAL POC: Colleen Marrese (colleen.m.marrese@jpl.nasa.gov)

Cathode Spots in Vacuum Arcs Create Extreme Plasma Environments

Vacuum Arc Electron Emission Processes

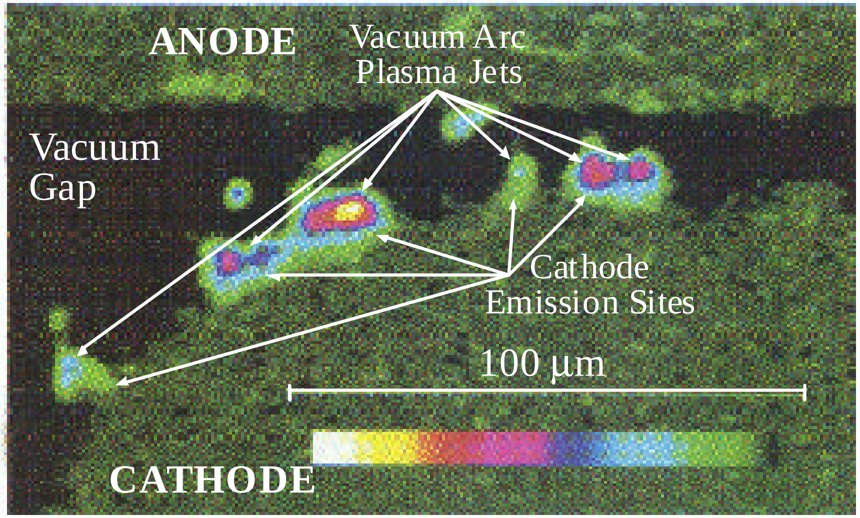


Site Initiation
Field emission from micropoint or dielectric inclusion.

Explosive Evaporation
Excessive joule heating in micro-emission site generates plasma by explosive vaporization.

Crater Formation
Power deposited by joule heating and ion bombardment heats surface to extreme temperatures. Electrons emitted by thermal-field emission.

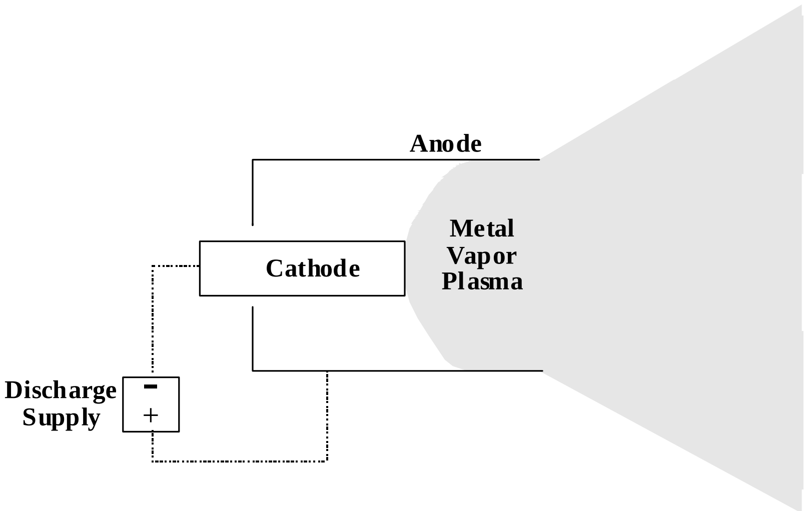
New Site Formation
Decreasing power density leads to site extinction and field emission at a nearby micropoint causes spot to shift.



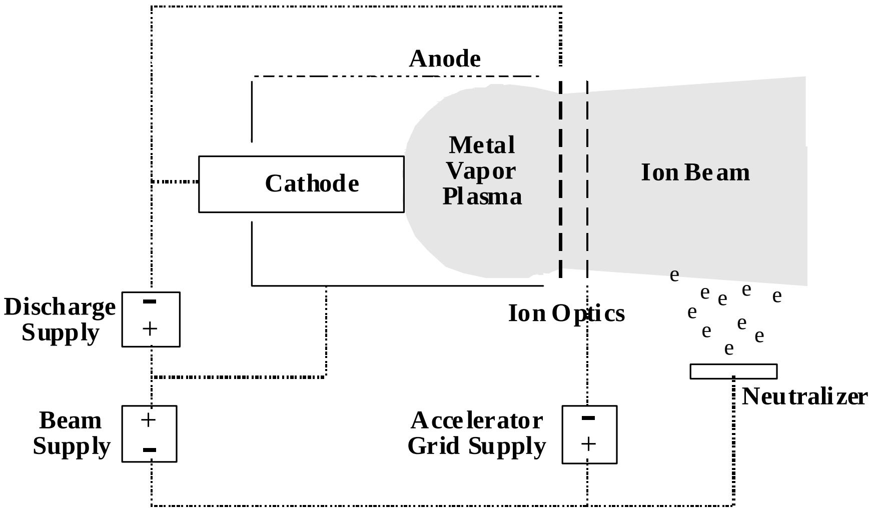
Laser absorption image shows ultra-high density plasma plumes created by cathode emission sites in a vacuum arc

- Vacuum arcs generate environments with unique properties
  - Current densities of 10^8 A/cm^2
  - Surface heat fluxes of 10^8--10^9 W/cm^2
  - Plasma densities of 10^{20}--10^{21} cm^{-3} (nearly the density of the solid metal!)
  - Nearly 100% ionization of metal vapor
  - Plasma expansion velocities of 10^4 m/s
- Pressure ionization, not electron bombardment processes, creates plasma efficiently in a tiny volume

Exploiting Extreme Conditions in Vacuum Arc Plasmas for Propulsion



Schematic of a vacuum arc thruster



Schematic of a vacuum arc ion thruster

CONCEPT

Metal vapor plasmas can be used to produce thrust in several ways

- Direct thrust from plasma plume expansion
- Electrostatic or electromagnetic acceleration of the dense plasma

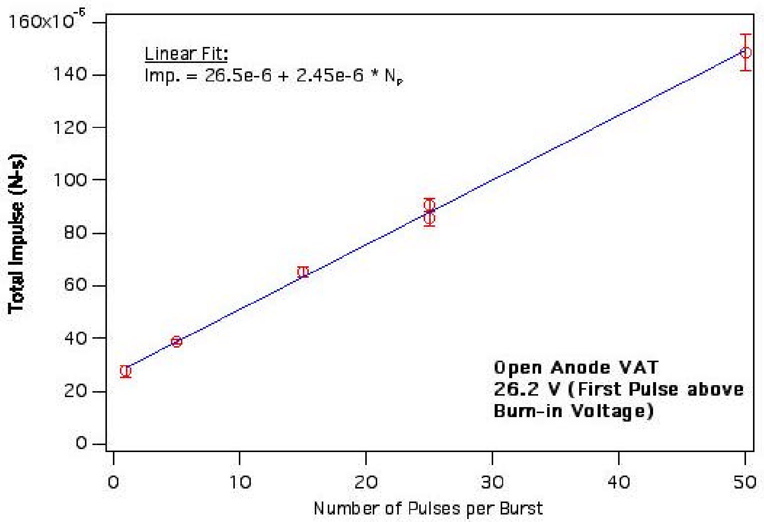
ADVANTAGES

- Vacuum arc plasma sources provide unique scaling advantages
  - No magnetic field required to confine or generate plasma
  - Plasma is created in small volume
  - No gas feed system is required
  - Discharge current can be tailored to produce wide range of plasma densities
- Plasma plume expansion allows higher current density extraction through ion optics

APPLICATIONS

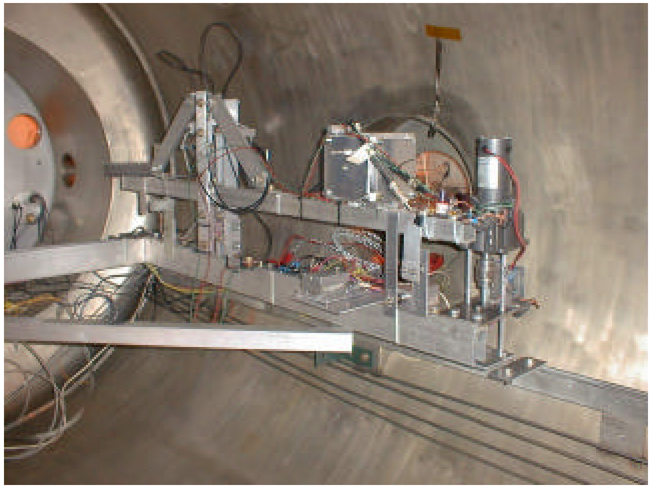
- Miniaturized thrusters for microspacecraft applications
- Very high density plasmas may enable very high power thrusters

Vacuum Arc Thruster Thrust Measurements Show Repeatable, Small Impulse Bits

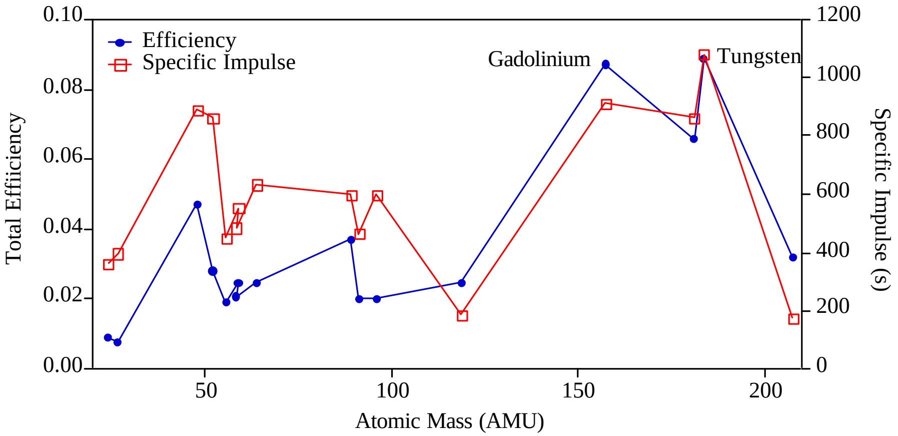


Impulse measurements for a titanium cathode

- Direct impulse measurements for impulses as low as 10 μN-s with <1 μN-s resolution were obtained for several VAT's supplied by Alameda Applied Sciences Corporation under a BMDO SBIR
- Preliminary measurements with VAT's show excellent agreement with a performance model which incorporates material properties, electrode geometry and metal vapor plasma properties
- VAT model suggests moderate efficiency and Isp for certain materials such as tungsten and gadolinium

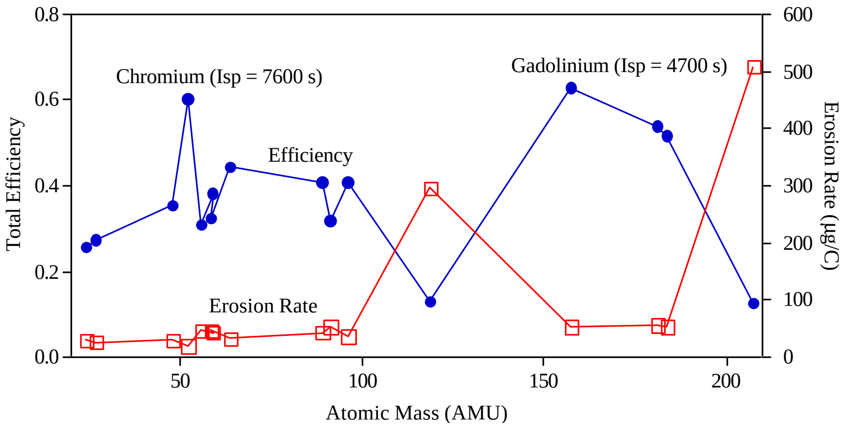


AASC VAT mounted on JPL micro-thrust stand

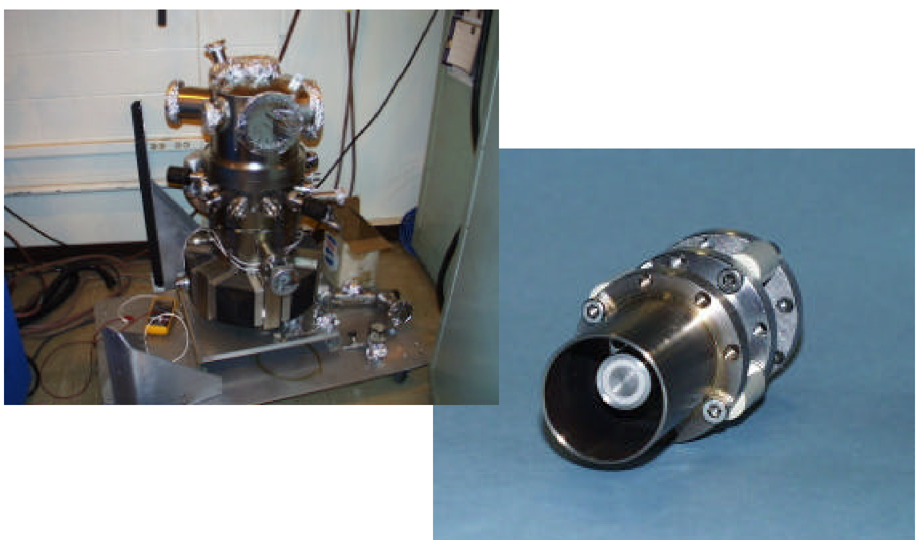


Model of VAT performance that incorporates plasma and electrode geometry effects

Preliminary Results Suggest Vacuum Arc Ion Thrusters Have Unique Advantages



Results of preliminary modeling suggest several candidate propellants



Vacuum arc UHV facility and thruster

FEASIBILITY ISSUES

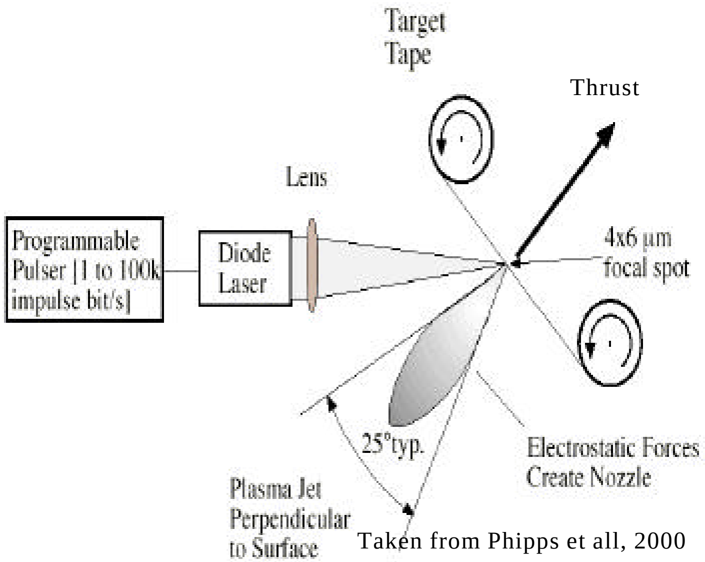
- Achieving high propellant utilization
- Interaction of high velocity plasma flow with ion optics
- Discharge triggering reliability
- Shorting in engine and spacecraft contamination from condensable vapor and droplet efflux

RECENT ACCOMPLISHMENTS

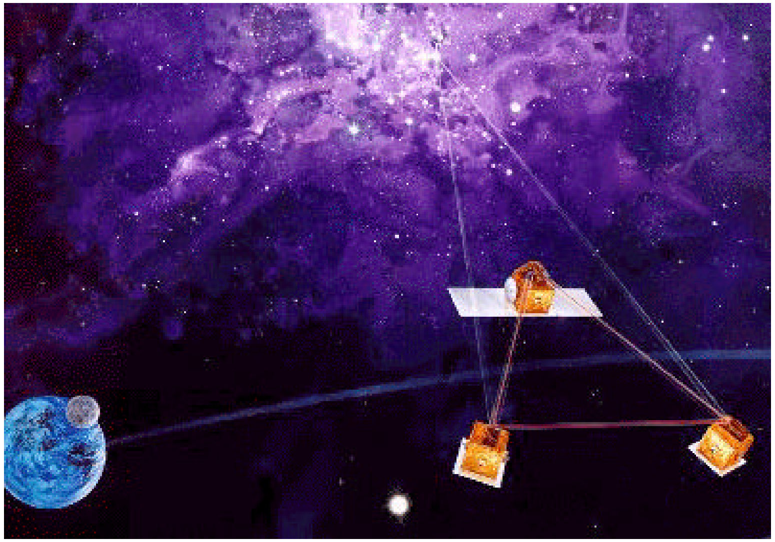
- Completed performance model which suggests high total efficiency is possible over broad range of thruster scales
- Initiated contract with Alameda Applied Sciences Corp. to test ignition reliability, characterize vacuum arc ion thruster performance and measure propellant properties
- Developed novel discharge power supply architecture
- Built engine and diagnostics to measure critical model parameters
- Completing assembly of UHV test facility, vacuum arc plasma thruster and discharge power supply

JPL TECHNICAL POC: Jay Polk (james.e.polk@jpl.nasa.gov

Laser Ablation Thrusters Can Provide Compact, Efficient Attitude Control Systems



Taken from Phipps et all, 2000



CONCEPT

- A pulsed laser produces thrust by ablating a small amount of material

ADVANTAGES

- Ablation process is very efficient with a high thrust-to-power ratio and large specific impulse value
- System requires less than 10 W steady-state
- Laser and optics have a mass less than 1 kg
- Does not require a neutralizer, high voltage power supply, or external heater
- Propellant can be a metal, polymer, liquid, thin foil or even unneeded spacecraft parts

POTENTIAL APPLICATIONS

- Fine pointing and positioning of space interferometer systems
  - Laser Interferometer Space Antenna (LISA)
  - Space Interferometry Mission (SIM)
  - Terrestrial Planet Finder (TPF)
- Attitude control of microspacecraft

Laser Ablation Thruster Feasibility Assessment by Modeling and Testing

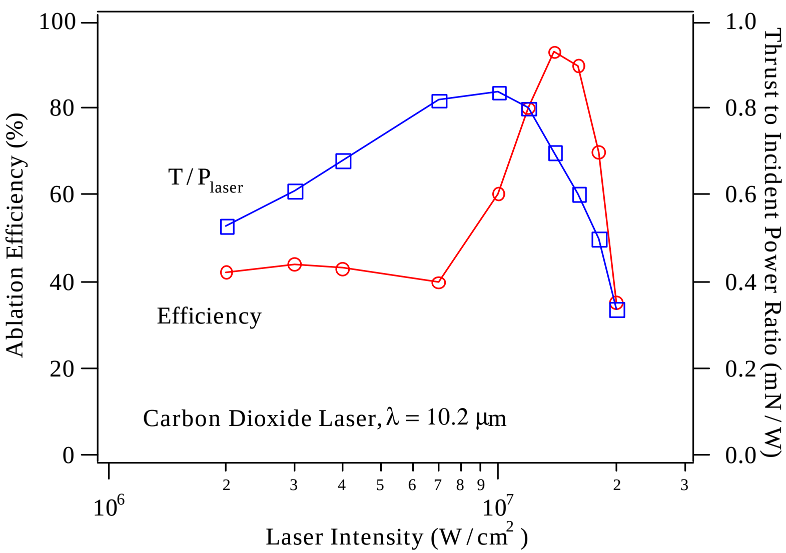
FEASIBILITY ISSUES

- Efficiency and dry mass of complete system
- Laser component and propellant feed system
- Contamination of optics and spacecraft surfaces

FY00 ACCOMPLISHMENTS

- Completed feasibility study and laser technology survey
- Diode lasers provide a compact, efficient light source in an all solid-state package that operates at less than 5 volts
- Highly viscous liquid micro-nozzles can provide a stationary propellant source without any moving parts
- Purchased a diode laser to pump an integrated Nd:YAG chip to produce higher pulse intensities at low power
- Developing performance models based on ablation physics and state-of-the-art laser technology
- Developing a nano-Newton Thrust Stand for future LAT system performance characterization

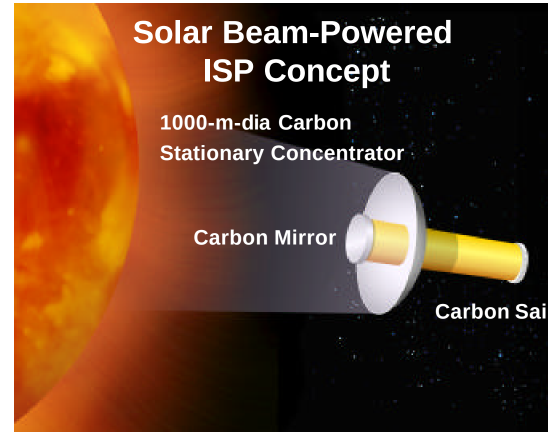
JPL TECHNICAL POC: John Ziemer
(john.k.ziemer@jpl.nasa.gov)



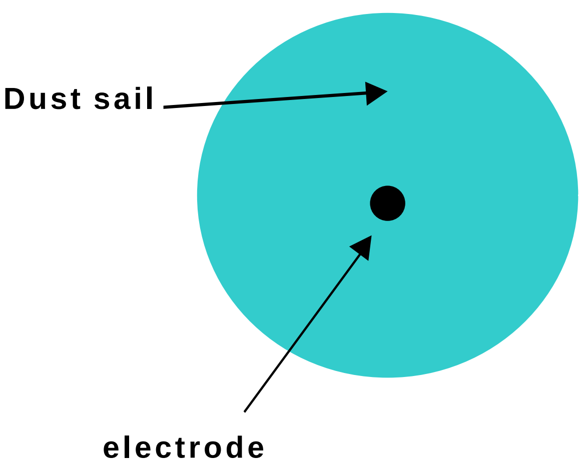
Performance Assessment:
- Larger CO_2 laser systems have been tested
- Ablation efficiency can be as high as 90%
- Thrust > 1 mN using < 10 W of laser power
- Minimum I_{bit} < 10 nNs for a single pulse
- Specific impulse can be over 1000 s

The APC Program Supports a Broad Range of Sail Activities

Hoop Sail Development•
- Completed 54 element sail
- Completed dynamics simulation
- KC 135 deployment test scheduled for April 16



Self-Deploying Carbon Sail Experiment
- Completed concept development and proposal for NASA KC 135 program (MIT)
- Proposals now in review



Electrostatic Dust Sails
- Concept for ultra-lightweight sail composed of reflective particles electrostatically coupled to spacecraft

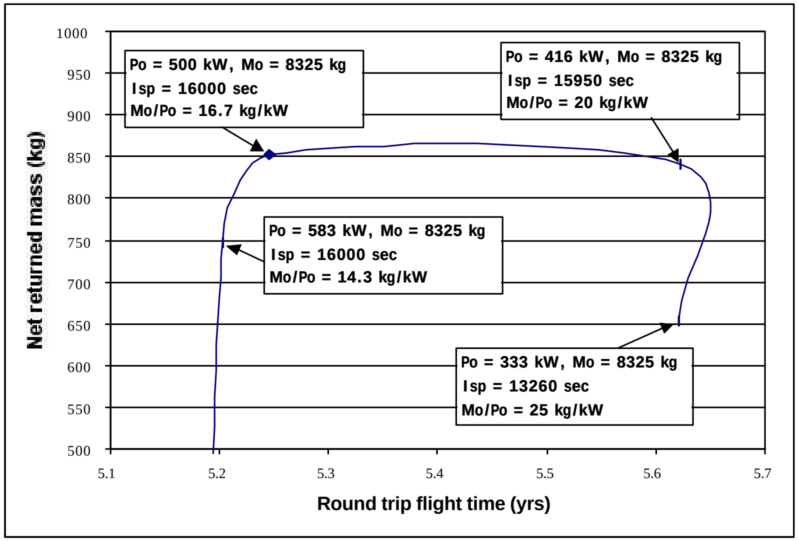
Solar Beam-Powered Sails
- Completed preliminary assessment of simple optics

Mars Cargo Studies
- Completed systems analysis of Mars cargo flights using large solar sails and M2P2 magnetic sails

Microwave Sail Feasibility Experiments
- Completed direct measurements of thrust due to microwave photon pressure on carbon fabric sails

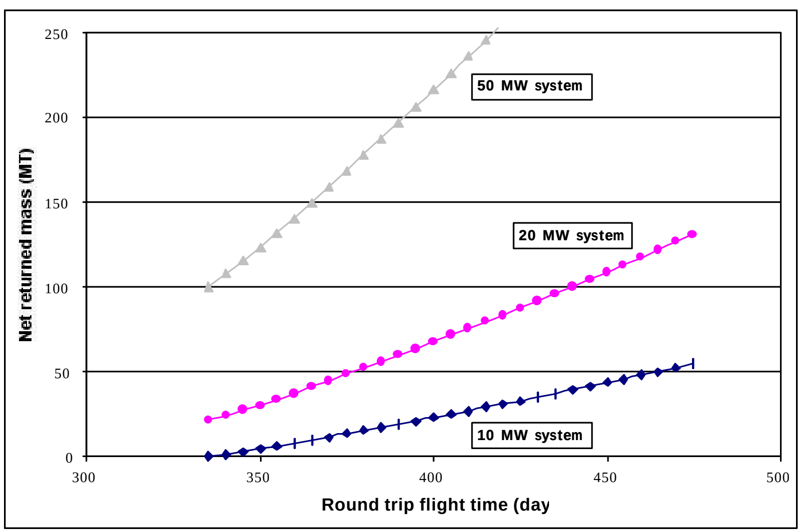
Wed, 8:00 "Solar and Electromagnetic Sails for the Mars Cargo Mission," Bob Frisbee
Wed, 8:20 "Summary of Recent Activities in Solar Sail Propulsion," Charles Garner
Wed, 9:50 "Spin and Deflection Measurements of Microwave-Driven Sails," John Ziemer

Advanced NEP Power Systems Can Provide Dramatic Benefits

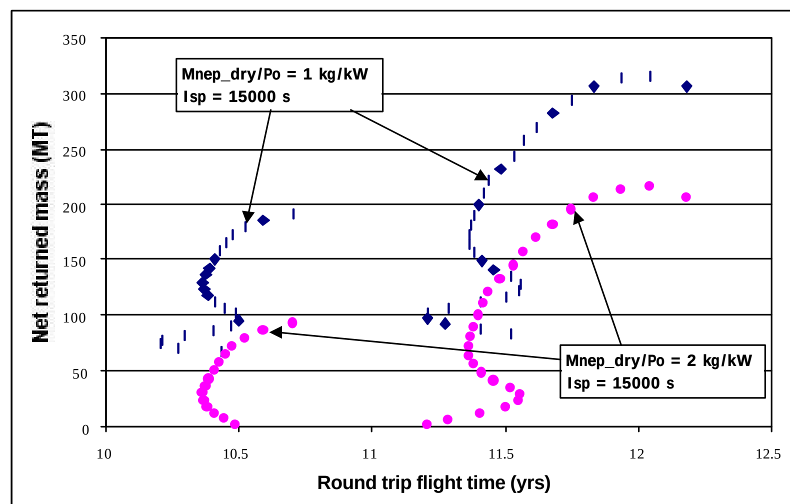


Near-Term Power Systems Enable Fast Outer Planet Sample Return Missions (Example: Europa)

- Detailed systems analysis of NEP missions used to study an evolutionary approach to solar system exploration
- Three power and technology regimes were studied
  - Near-term: 0.1-1 MWe, 18 kg/kWe
  - Mid-term: 1-50 MWe, 4.3-4.6 kg/kWe
  - Far-term: 100 MWe, 0.5 kg/kWe
- Study results demonstrate missions enabled by NEP:
  - Outer planet sample return missions
  - Kuiper belt and interstellar precursor rendezvous missions
  - Fast piloted missions

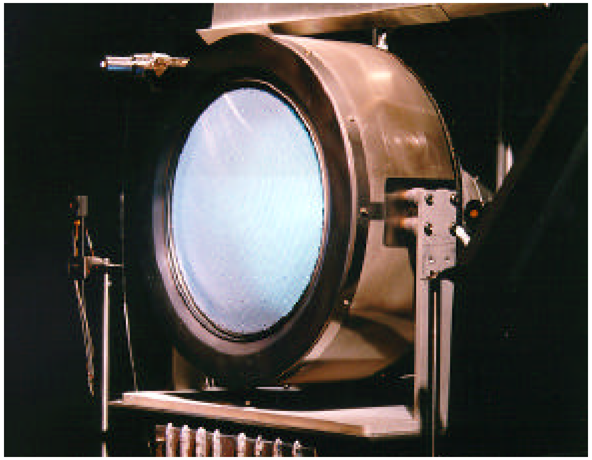


Mid-Term Power Systems Enable Fast Piloted Mars Missions

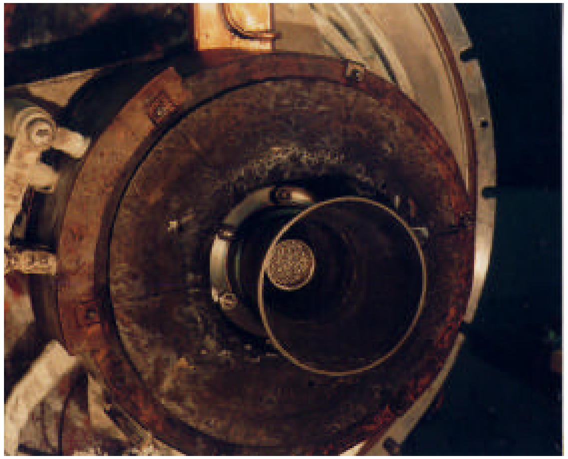


Advanced Multimegawatt Systems Open up the Solar System To Human Exploration (Example: Neptune)

Unparalleled Power Processing Capability Enables New Missions



2.3 kWe NSTAR Ion Thruster



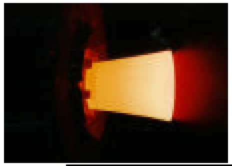
200 kWe MAI Li- LFA

Electromagnetic acceleration process allows >40 times the power of the NSTAR ion engine to be processed in the same volume

Very high power propulsion systems enable many far-term missions:

- Interstellar precursor missions
- Fast robotic and piloted outer planet missions
- Orbit-raising heavy payloads in Earth orbit
- Piloted Mars and Mars cargo missions

Recent Experimental and Theoretical Results Show Path to MWe Plasma Thrusters

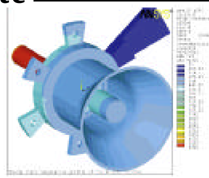


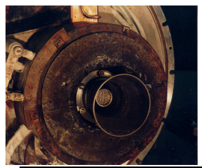
POWER

200 kWe
Steady State

- Anode Texturing
- Heat Pipes

1 - 5 MWe
Steady State



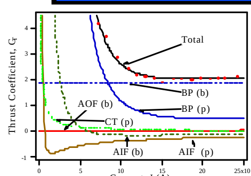


PERFORMANCE

η = 50%
Isp = 4000 s

- Lithium Propellant
- Active Turbulence Suppression

η = 60%
Isp 8000 s

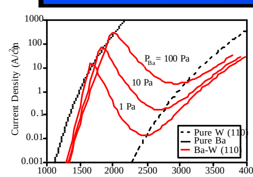


LIFETIME

100's of Hrs
At 3000 A

- Multi-Channel Hollow Cathodes
- Barium Addition

10000 Hrs
At 20000 A

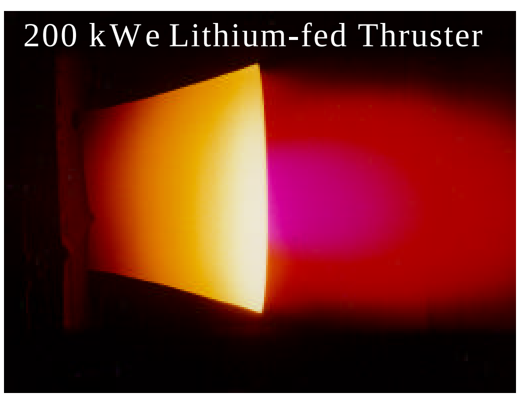


PLUME CONTAMINATION

10^{-8} g/cm^{2}s
at 0.3 m

- Plume Shields
- Booms

10^{-10} g/cm^{2}s
at 30 m

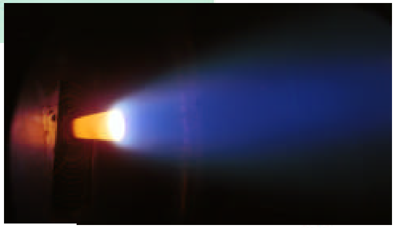


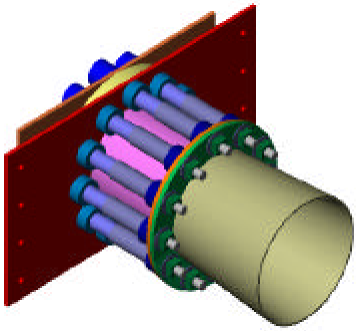
STATE OF THE ART

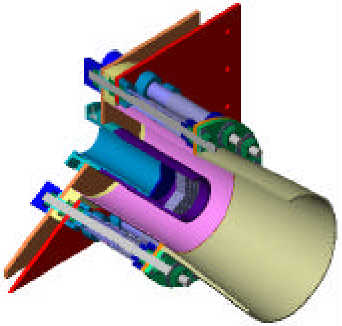
MULTIMEGAWATT TECHNOLOGY

Multi-Megawatt Propulsion with Lithium-fed Lorentz Force Accelerators

- **Specific Technical Objective(s)**:
  - Demonstrate operation at high power levels (0.5 - 1 MWe)
  - Evaluate engine performance at high power
  - Achieve required engine lifetime (3000-10000 hours)
  - Demonstrate tolerable levels of lithium backflow (acceptable levels of deposition on sensitive spacecraft surfaces)
- **Approach**:
  - Design and build testbed engines based on US and Russian experience
  - Experimentally evaluate engine performance, life-limiting phenomena and lithium plume characteristics
  - Develop and validate models of LFA discharge plasma and electrodes. Use discharge model to optimize performance and model heat loads to electrodes. Use electrode thermal models to evaluate engine lifetime.
  - Develop and validate plume model using the discharge code to provide the source function. Use this code to evaluate the risk of spacecraft contamination.







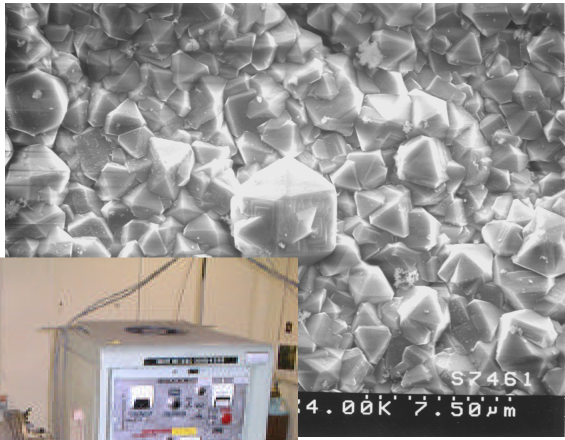
- **Accomplishments**:
  - Completed design of a 500 kWe, radiation-cooled, steady state engine
  - Completed subscale tests of critical engine components
  - Currently fabricating 500 kWe engine
  - Completed integration of liner and installation of vacuum system and power supplies in test facility to allow high power testing with lithium
  - Completed fabrication and calibration of lithium feed system (Princeton)
  - Completed initial tests of 30 kWe-class lithium thruster build by RIAME-MAI (Princeton)
  - Completed initial MHD code employing characteristic flux splitting to model LFA discharge (Princeton)
- **JPL Technical POC**: Jay Polk, JPL, (818) 354-9275, james.e.polk@jpl.nasa.gov

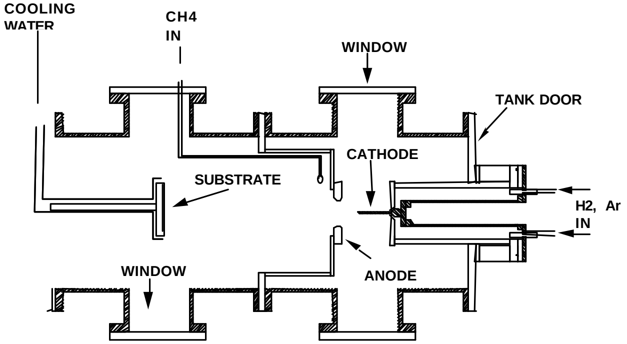
Wed, 4:00 PM: "Design and Fabrication of a 500 kWe, Li-fed Lorentz Force Accelerator," Jay Polk

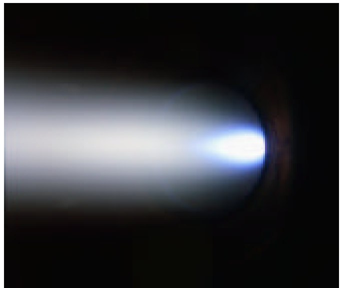
Wed, 4:20 PM: "Lithium Lorentz Force Accelerator Research at Princeton University," Edgar Choueiri

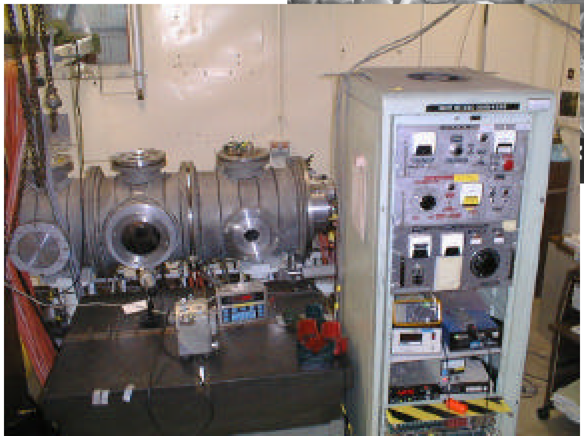
MPD Assisted Chemical Vapor Deposition for Rapid Diamond Film Growth

- **Principal Investigator**: John Blandino, JPL, (818) 354-2696, john.j.blandino@jpl.nasa.gov
- **Specific Technical Objective(s):**
  - Evaluate the benefits of diamond film for advanced propulsion applications (sputter rates)
  - Investigate use of MPD plasma source for diamond film synthesis (gas ratios, injector position)
  - Investigate potential benefits of substrate biasing
  - Investigate influence of jet velocity and dissociation/ionization level on chemical kinetics in free stream, boundary layer and substrate surface.
- **Approach**:
  - Sputter yield measurements over energy range of interest to mitigate erosion
  - Laboratory evaluation of MPD assisted diamond vapor deposition
  - Analysis of gas-phase and heterogenous chemical kinetics using Chemkin Software
- **Accomplishments:**
  - Sputter yield measurements completed (to be published in Diamond and Related Materials)
  - Received provisional patent for MPD-CVD process
  - Laboratory evaluation of MPD assisted diamond deposition completed
  - Completed kinetics modeling of process
  - Defended PhD thesis at Caltech (today!)









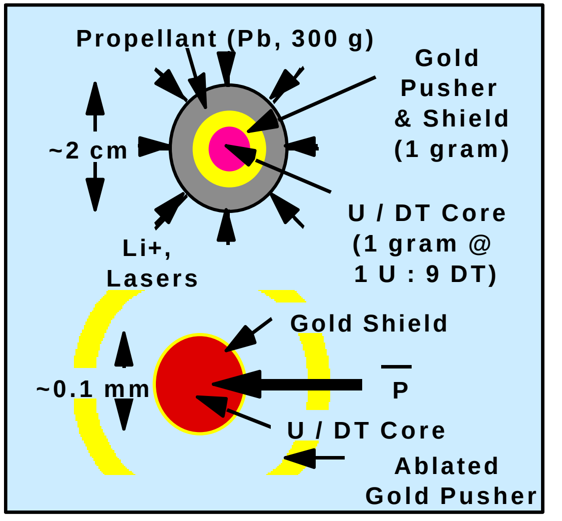
ICAN Fusion Target and Systems Study: Exploiting DOE Expertise to Assess Feasibility

- **Principal Investigator**: Dr. Charles Orth, LLNL, (818) 354-2696, orth2@llnl.gov

- **Specific Technical Objective(s)**:
  - Evaluate the ICAN target design
  - Develop an improved target design and assess feasibility of concept based on new target design
  - Determine if antimatter-catalyzed fission ignition reduces the driver mass significantly

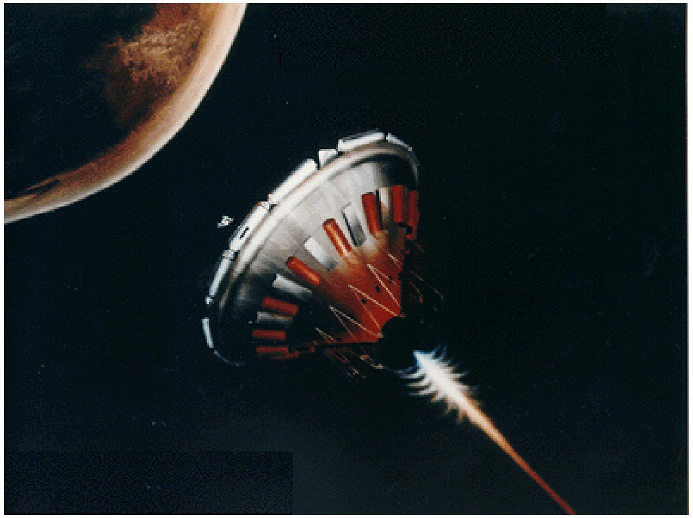
- **Approach**:
  - Use approximate methods developed for ICF target design to evaluate ICAN concept
  - Use detailed design codes developed for ICF and stockpile stewardship program to improve target design
  - Use modeling results to identify antiproton delivery issues, target yield and required compression
  - Apply experience with ICF drivers to evaluate impact of ICAN approach on driver mass

- **Accomplishments**:
  - Contract initiated in June, 2000
  - Review of previous target analysis completed
  - Progress delayed by reorganization associated with the National Ignition Facility



Systems Study of Magnetized Target Fusion (MTF) Propulsion

- **Specific Technical Objective(s)**:
  – Evaluate mission benefits and technology requirements / systems-level impacts of the use of a Magnetized Target Fusion (MTF) propulsion system for a piloted Mars mission



- **Approach**:
  – Identify systems-level parameters of MTF device (Isp, thrust, mass, power, gain, radiation, etc.)
  – Combine/integrate MTF device into a complete fusion propulsion system
    - Use inputs from on-going fusion propulsion studies (C. Williams, GRC and F. Thio, MSFC)
  – Model mission performance (mass and trip time) and compare to other fusion propulsion concepts

- **JPL Technical POC**: Robert H. Frisbee, JPL, (818) 354-9276, robert.h.frisbee@jpl.nasa.gov

The Advanced Propulsion Concepts Website: Updating a Valuable Resource

- **Specific Objectives**:
  - Update existing website to reflect changes since last revision (1997)
  - Add new concepts description, art, etc. (e.g., M2P2, etc.)
  - Add links to other programs (e.g., MSFC/USAF Solar Thermal, GRC Breakthrough Physics)

- **Approach**:
  - Use updates from AIAA Future Flight Class slides
  - Obtain/prepare materials on new concepts from literature
  - Obtain and implement links to other programs

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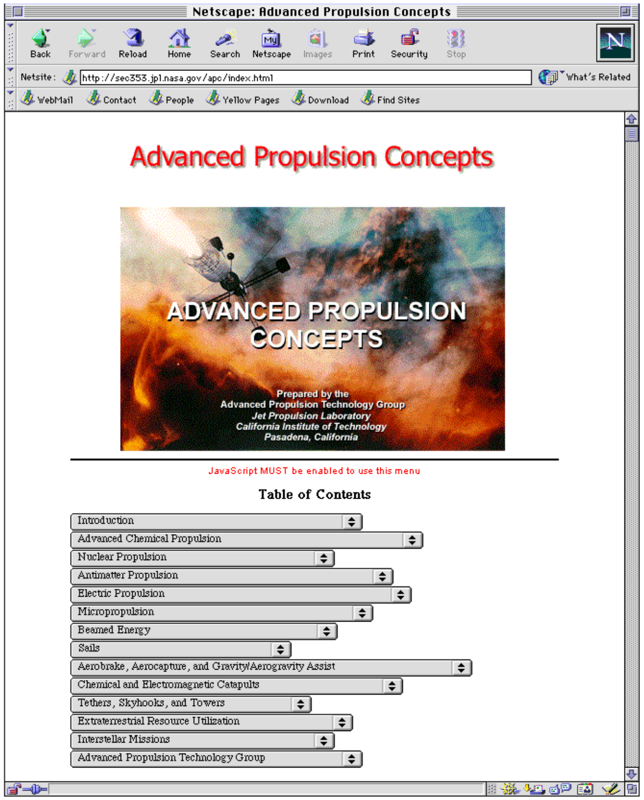

http://sec353.jpl.nasa.gov/apc/